Presented at the APS Centennial meeting ATLANTA, March 1999
Heavy Ion Minisymposium, to appear in proceedings,
R. Seto, ed., World Scientific, (Singapore 1999).

$\mathbf{B_c}$ MESONS AS A SIGNAL OF DECONFINEMENT

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We investigate the fate of bottom quarks produced in heavy-ion collisions at RHIC. Examining both the direct capture of a charmed quark, and multi-step processes, where the B_c meson is formed in a sequence of quark capture and exchange reactions, we find: a) that a sufficiently high number of B_c's will be produced to generate a detectable tri-lepton signal, and b) that the production rate of B_c's is highly sensitive to the properties of the deconfined source. A flavor-independent potential model, which includes color screening effects, is used to study the propagation of a B_c in a quark-gluon fireball and to compare this behavior with that of J/ψ mesons.

1 Introduction

We argue here that RHIC energies should create physical conditions conducive to the use of B_c mesons as a new observable of deconfinement and quark-gluon plasma (QGP) formation, in spite, and also because of the fact that elementary processes lead to the small branching ratio [1],

$$R_{Bc}^{\rm elem} = \frac{B_c + B_c^*}{b\bar{b}} \simeq 10^{-4}\text{–}10^{-5}\,. \tag{1}$$

The fast electromagnetic decay of the vector meson B_c^* allows us to ignore here the distinction between the scalar and vector mesons. The CDF collaboration recently announced the discovery of the B_c system [2,3]. Their announcement was based on careful analysis of 20 events with characteristic three-charged particle tracks expected from the decay $B_c^{\pm} \to J/\psi + l^{\pm} + X$. The CDF collaboration determined values for both the mass and the lifetime of the ground state,

$$M(B_c) = 6400 \pm 390 \pm 130 \text{ MeV}, \qquad \tau(B_c) = 0.46^{+0.18}_{-0.16} \pm 0.03 \text{ ps}. \tag{2}$$

Allowing that either the c quark or the $\bar{\rm b}$ quark can decay while the other is simply a spectator, or that the c quark and the $\bar{\rm b}$ can annihilate into an intermediate vector boson, the weak decay width of the ground state of the B_c is the sum of three terms, namely,

$$\Gamma(B_c \to X) = \Gamma(\bar{b} \to X) + \Gamma(c \to X) + \Gamma(\text{annih}). \tag{3}$$

Thus our potential model calculation of section 3 yields $\tau(B_c) = 0.36 \pm 0.05\, ps$, which agrees with the CDF result. Our calculation of the mass of B_c described below in section 3 is also in good agreement with the CDF measurement.

This lifetime allows B_c mesons with sufficient transverse velocity to escape the beam centroid and thus produce a secondary tri-lepton vertex, which serves as a distinctive feature for identifying the decay. It is noteworthy that the lifetimes of all B_c states below threshold are much longer than their counterparts in charmonium or the upsilon system because flavor conservation prevents decays through gluon annihilation diagrams.

In a QGP environment at RHIC the formation of this 'stable' exotic B_c meson is facilitated by the ready availability of charmed quarks. We explore here the production enhancement of B_c with a view at both a study of its properties and as diagnostic tool of the QGP state.

2 $\mathbf{B_c}$ Production and Survival in a Nuclear Fireball

Although the energy available to the individual nucleons in a typical RHIC experiment is not as high as that at Fermilab, the formation of QGP presents an environment that should enhance the production of bound B_c states, since both b and c quarks should be able to propagate freely. At typical RHIC energies parton fusions,

$$g + g \rightarrow Q + \bar{Q}, \qquad\qquad q + \bar{q} \rightarrow Q + \bar{Q}, \tag{4}$$

should produce a supply of propagating charmed and occasional b and $\bar{\mathrm{b}}$ quarks with energies less than 10 GeV. The recent calculation of Mustafa *et al.*[4] shows that gluon bremsstrahlung provides a very efficient mechanism for energy loss and that most of the heavy quarks with energies in this range should stop in a typical distance of 2 fm. An adequate flux of charmed quarks would lead to the production of B_c states by an inelastic scattering accompanied by gluon bremsstrahlung.

Since the strange quark flux is probably about 100 times larger than the charmed quark flux, B_s states should be formed much more frequently than B_c states. Because of the tight binding of the B_c states, quark exchange $B_s + c \leftrightarrow B_c + s$ is an exothermic reaction, and we expect this two-step process to be also an important mechanism for production of B_c's.

Using a total $\mathrm{b\bar{b}}$ production cross section of 1.7 microbarns and an overlap function appropriate for a head-on Au-Au collision at 100 A GeV, we get a $\mathrm{b\bar{b}}$ production rate of 0.05 pairs per central collision. The abundance of $c\bar{c}$-pairs has been estimated to be 200 times bigger, and our population evolution calculations yield a much greater fraction R_{Bc} than has been obtained for the

one step reactions, Eq. (1). A further enhancement of the relative B_c-yield arises from multi-step processes described above, operating in particular in the final stages of the QGP evolution. Our calculations show in presence of plasma a major change in the value R_{Bc}, Eq. (1), and thus a major increase in the absolute yield of the B_c mesons.

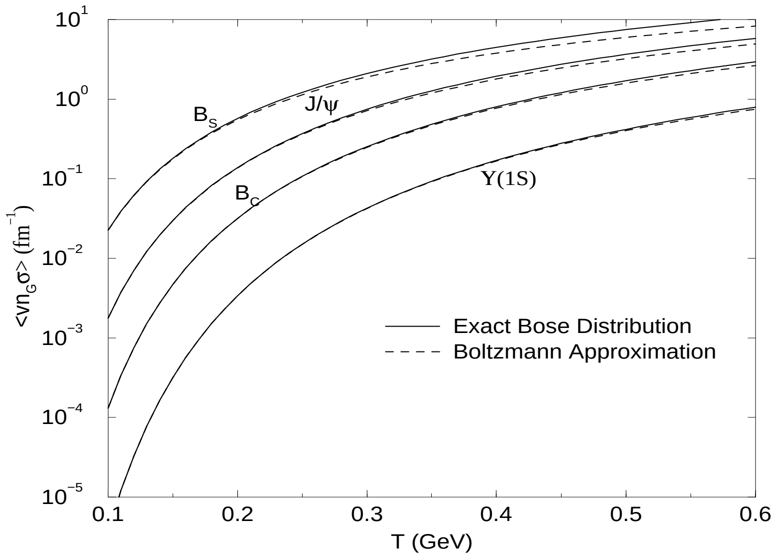

Figure 1: Quarkonium dissociation rates as functions of temperature.

We cannot describe here all the intricacies of the population evolution equations that establish the final production rates of the B_c. We mentioned already that there are several channels of production. Beyond that the issue is to assess the prospects for the survival of the B_c state in the hot parton environment. Using Kharzeev's approach[5], we have calculated the quarkonium dissociation rates for J/ψ, B_c and $\Upsilon(1S)$, as shown in Fig. 1. The curves there indicate that B_c should travel 5 to 10 times further than J/ψ at $T = 300\,\mathrm{MeV}$. It is worth noting that the probability of dissociation of the B_c at $T = 400\,\mathrm{MeV}$ is about the same as that of J/ψ at $T = 300\,\mathrm{MeV}$.

3 Potential Model Approaches to the $\mathbf{B_c}$ System

Another way to understand the unusual stability of the B_c mesons in the plasma phase is to consider its bound state structure. The rich spectra of bound states of charmonium and the upsilon system below the flavor thresholds[6] provide enough information to determine the parameters of a nonrela-

tivistic potential model for heavy quarks. The assumption of flavor independence extends this model to the B_c system. We describe here one such recent calculation[7] incorporating a model of a running coupling constant effects in the central potential and the full radiative one-loop expressions supplemented by the Gromes consistency condition to incorporate non-perturbative effects in the spin-dependent potentials: these calculations provided an excellent fit of the upsilon levels (avg. dev. $= 4.3\,\mathrm{MeV}$), a good fit of the charmonium levels (avg. dev. $= 19.9\,\mathrm{MeV}$) and a good account of the leptonic widths below threshold. The model predicts a ground state energy of $M(B_c) = 6286^{+15}_{-6}\,\mathrm{MeV}$ and that this state is 820 MeV below the threshold for heavy-light flavored meson production. Notably, the ground state of B_c is expected to be about 150 MeV more tightly bound than the ground state of charmonium, and one thus would expect it to be more likely to survive QGP environments with temperatures around 300 MeV.

To extend the potential model concept to QGP, one needs a means to consider the effects of color screening. Thus, we follow the the approach of Karsch, Mehr and Satz [8], who introduce color screening effects with an exponential damping factor. Their analysis begins with a Coulomb plus linear potential, which describes the $T = 0$ limit. Such a potential is known to give an adequate account of heavy-quark spin-averaged energies [9]. Their inverse Debye screening length parameter $\mu(T)$ describes the temperature dependence of color screening. It also allows for deconfinement by parameterizing the melting of the string tension. The Karsch-Mehr-Satz form for the central potential is

$$V_{\mathrm{KMS}}(\mu(T), R) = A\frac{(1-e^{-\mu r})}{\mu} - \kappa\frac{e^{-\mu r}}{r}. \tag{5}$$

From the large distance limit, the energy required to dissociate the system is

$$E_{dis}(\mu) = m_b + m_c + \frac{A}{\mu} - E_{bc}(\mu)\,, \tag{6}$$

where the binding energy $E_{bc}(\mu)$ is obtained solving the Schrödinger equation with $V_{\mathrm{KMS}}(\mu(T), R)$, Eq. (5). Deconfinement is achieved when the dissociation energy vanishes, thus defining the critical value of μ. Our results for the dissociation energies of the three lowest B_c states are shown in the top portion of Fig. 2. There one sees that $\mu_{crit}(1S) = 840\,\mathrm{MeV}$, almost 200 MeV higher than the corresponding quantity for J/ψ. The μ dependence of the sizes of these 3 lowest B_c states are shown in the bottom portion of Fig. 2. For any given value of μ, the dissociation energy for the B_c state is larger than the value for the corresponding state in charmonium, and the average radius is smaller.

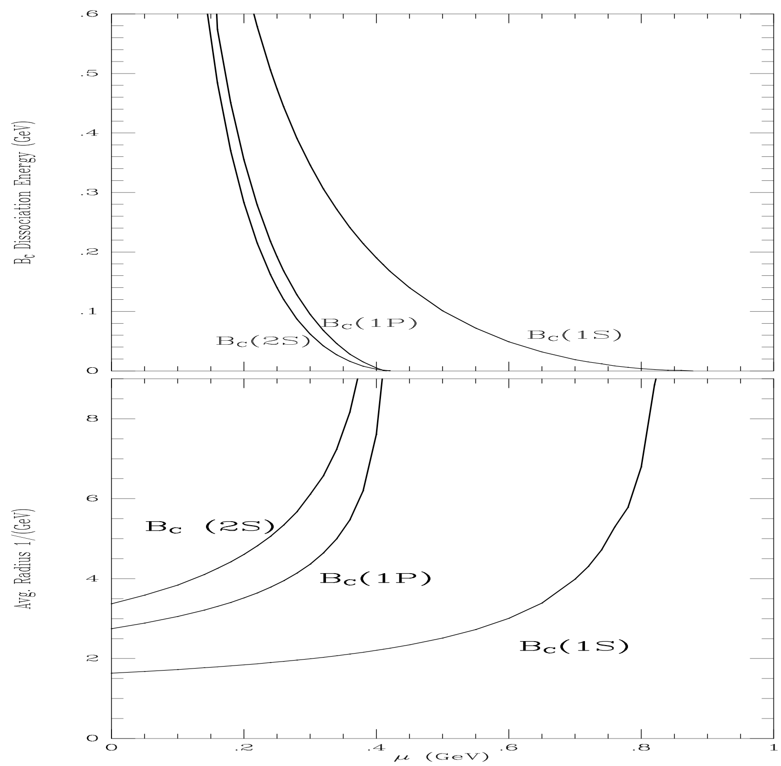

Figure 2: Top: B_c dissociation energies, bottom: B_c radii as functions of inverse screening length.

4 Outlook and Conclusions

The computation of the ratio R_{Bc}, Eq. (1), in the deconfined QGP environment poses a challenge, and our estimates yield at present a few percent. In any case a very significant, by a factor 100–1000, and observable enhancement over elementary processes is to be expected. Based on the known parameters of the RHIC we have worked out some interesting numbers shown in table 1. The reason that the chemical non-equilibrium for charm is leading to a greater yield is the fact that the directly produced charm is here dominating the thermal production. There is practically no re-annihilation of charmed quarks as plasma cools down and hence the significant increase of the tri-lepton channel decay yield of the B_c.

Table 1: RHIC yields for several heavy quark systems.

observable	first year	design luminosity
$c\bar{c}$-pairs	$2.8\,10^8$	$6.5\,10^9$
$b\bar{b}$-pairs	$1.2\,10^6$	$3.2\,10^7$
$J/\Psi \to \mu^+\mu^-$	$1.6\,10^5$	$3.9\,10^6$
$\Upsilon(1s) \to \mu^+\mu^-$	140	3800
$B_c \to J/\Psi + l\nu$	no	QGP
$\to \mu^+\mu^- + l\nu$	0.05–0.18	1.5–4.9
$B_c \to J/\Psi + l\nu$	therm+chem. equil.	QGP
$\to \mu^+\mu^- + l\nu$	18	490
$B_c \to J/\Psi + l\nu$	only prim. $c\bar{c}$	QGP$(T = 400\,\mathrm{MeV})$
$\to \mu^+\mu^- + l\nu$	235	6400
$B_c \to J/\Psi + l\nu$	only prim. $c\bar{c}$	QGP$(T = 200\,\mathrm{MeV})$
$\to \mu^+\mu^- + l\nu$	1000	27,000

Our conclusions are:
(1) The larger binding energy of the B_c system and the availability of the primary-interaction charmed quarks facilitates production and stability of the B_c meson;
(2) The B_c should be observable at RHIC (as well as at LHC-Alice), and the study of the elementary properties of the B_c mesons appears possible;
(3) The dynamics of the B_c system in plasma (given its smaller size and greater binding) is different from that of J/ψ, and thus B_c should produce information that is complementary to that produced by J/ψ, and $\Upsilon(1s)$;
(4) There is potential for a 'smoking gun' evidence of deconfinement indicated by a significant enhancement of R_{Bc}, and thus it is important to evaluate this quantity theoretically and measure it experimentally in QGP environment.

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